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Structural Reliability Assessment Methodology – Why now?

by

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Abstract

Prior to the advent of the aging aircraft problem, the criterion for ensuring USN airframe safety was a damage index labeled FLE (Fatigue Life Expended.) In retrospect, over several decades the application of the FLE criterion has provided an exemplary, cost effective, structural-safety record. However, with today's realities, the structural engineering community is being directed to maintain airframes longer than originally envisioned and fly beyond the FLE criterion. Consequently, a reliability assessment methodology is being developed based on a total life concept. The reliability assessment will provide management with the needed technical support in order to make informed decisions regarding aging airframes and maintenance demands.

Introduction

Navy air vehicles operate from floating bases, with run-ways 1/10 the length of land-based runways, perform missions at altitudes barely clearing the waves, and are on deployed, away from maintenance hangars, for months on end. The fundamental constraint with respect to life management is that the limited space and broad theater of operations of aircraft carriers restrict routine inspections for fatigue cracks. Hence the Navy strives to accept air vehicles into their inventory that are designed to obtain their service lives without the need for significant carrier inspection and repair programs.

Consequently, a Safe-Life approach has been used to design all Navy aircraft to withstand fatigue loading as documented in [1]. The underpinnings of the safe-life force management philosophy have been the formulation of a service life limit as defined by the fatigue life expended (FLE) index and the application of a tracking program.

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Service Life Limit

Service life limits are established for an aircraft based on operational requirements, design criteria, technical analysis and fatigue test results. In the simplest of terms, testing an early production aircraft to a severe flight-by-flight loading until it fails or the test budget is exceeded validates the service life. The cracks are inspected fractographically and the flight hours to a crack length of 0.01" are noted. This is nominally the time-to-crack-initiation. Failure is defined to be crack initiation, the 0.01" crack.

For each critical cracking location, the component service life equals the time-to-crack-initiation divided by two. For critical locations that have not cracked, service life equals the test duration divided by two. The factor of two is known as the factor of uncertainty on life [2]. It is a ratio of the failure life to the desired service life,

$$\text{Factor of Uncertainty} = \frac{\text{Failure Life}}{\text{Desired Service Life}}$$

where life is a unit of time measured by percentage of fatigue life expended (FLE), for example. Factors of uncertainty are used to provide a degree of assurance that uncertainties in materials, fabrication, and service do not cause failure. The factor of 2 provides approximately a 1/1,000, single aircraft lifetime probability of failure [3].

The Test Spectrum

The most influential variable to establishing the demonstrated airframe service life is the fatigue test spectrum. Spectra were typically identified in the aircraft procurement specifications, but may now be "negotiated" as fallout from streamlined acquisition initiatives. USN aircraft currently under development employ a Nz spectrum based on the usage of similar type aircraft. Because, the empty weight and usage will most likely change over the 20+ years of a combat aircraft's life conservative assumptions must be made. The advent of fly-by-wire control systems, which may significantly change maneuver loads through reprogramming, provides further incentive for conservative point-in-the-sky assumptions.

The Fatigue Tracking

Fatigue predictions are performed from flight recorder data on most Navy and Marine fixed-wing air vehicles. Fatigue damage is reported as the fatigue life expended (FLE), an index relative to the spectrum test hours it takes to form 0.01" cracks and is calculated at five to nine locations for fighter/attack aircraft utilizing a strain-life approach.

Strain-life was first used to predict crack initiation on the F/A-18 aircraft in the 1980s and is now the standard of all FLE calculations. The strain-life method predicts the fatigue damage resulting

from the fluctuating local plastic deformation, or strains and has the primary advantages of being able to account for load sequence and residual stress affects.

The FLE tracking process is summarized in Figure 1. The four main elements of tracking are data collection, data reduction, damage calculation, and information dissemination. Load excursions are recorded on the aircraft. Aircraft have accelerometers that record the number of exceedances of a few g-levels the aircraft encounters. New aircraft are delivered with manufacturer-supplied multi-channel recorders. Older aircraft are being retrofitted with the Structural Data Recording Set, SDRS, a generic multi-channel recorder. These recorders allow load excursions to be saved in chronological order for input into the strain-life algorithm. Maintenance crews perform data recovery from individual aircraft. Depending on the air vehicle and recording set, data storage units fill up weekly. Data are sent monthly to Naval Air Systems Command at Patuxent River, where they are received for processing.

After the data are subjected to strict quality control measures, hysteresis loops are constructed from the stress history (Figure 2a). Hysteresis loops, created by plotting local stress versus strain, identify damaging events (Figure 2b). When the ranges and means of the closed loops are assembled from the hysteresis loops, equivalent strain amplitude is calculated and life is found from the strain-life relationship (Figure 2c). The damage fraction for the hysteresis loop is defined as the inverse of cycles to failure, $1/N_f$. When life has units of cycles, damage has units of inverse cycles (Figure 2d). The incremental damage is calculated by multiplying each of the $1/\text{life's}$ by the number of cycles having the same equivalent strain amplitude and summing them, as represented by the following equation, known as Miner's Rule,

$$\frac{\sum_{i=1}^{nt} n_i}{N_{fi}} = \text{Cumulative Damage}$$

Where N_{fi} are the individual cycles to failure corresponding to the i^{th} discrete group of strain amplitudes present in the counted strain history, n_i are the number of cycles at the i^{th} strain amplitude level, and nt is the total number of discrete strain amplitude levels.

According to Miner's rule, when the cumulative damage equals one, failure is predicted to occur. In applying this rule to naval aviation, failure is defined as the formation of a 0.01-inch crack, based on experience from the full-scale test. This linear damage summation method is widely used in fatigue algorithms, independent of sophistication of their damage equations. Open loops are typically included in the monthly incremental damage as half the damage of a closed loop, and are also saved for closing with future data. The level of residual stress to carryover from month to month of data receipt is always a topic of discussion among the engineers responsible for tracking, especially as lapses occur in data receipt and usage must be assumed.

Next the FLE is found by multiplying the cumulative damage by 200% (Figure 2d). This step allows the FLE at 100% to have the equivalent damage as the full-scale test component at half of its life, consistent with applying a factor of uncertainty of two. The FLE is presented as the percentage of life used toward failure. FLE is plotted versus flight hours, and aircraft are

nominally retired when FLE= 100% [Figure 3]. Recall that time- to- failure is defined as the time it takes to form a 0.01-inch crack. The FLE is the cumulative damage with the factor of uncertainty applied.

Future of Life Prediction for Aircraft Structural Components

What are the implications of our current approach to fatigue life estimation? We've had good experiences with our aircraft. Class A Mishaps due to structural failures are extremely rare. A reasonable estimate of occurrence is 1 incident every 15 million flight hours flown. The chances of an aircraft falling out of the sky for structural reasons is one tenth the chance that the pilot will be struck by lightning while taking a walk. But this is a statement of past events. What does this imply about the safety of future flights?

In the current socioeconomic climate, replacement planes are not guaranteed. Legacy airframes must last thirty, fifty, or more years, well beyond their FLE limits. As long as an aircraft is flying within its FLE limits, we know from the full-scale test experience where to expect cracking. Inspections are designed for these specific locations. The probability of crack initiation is small. Aircraft safety is conservative. As aircraft fly beyond their limits, we expect that cracks will form at other sites, not detected during testing. Inspections performed on airframes operating beyond their test-validated life are more general, less specific. Consequently, the trustworthiness of the inspections degrades. In other words, it's infinitely harder to find cracks if you don't know where to look. The inspection technique can be perfect, but will not have much value if we're looking in the wrong place. Life predictions are complicated by mission changes for the fleet and modifications to the power plant or structure. We need to account for the random aspects of loads in addition to exceeding the original design life. We need a new tracking approach.

Flying more than the flight hours associated with 100% FLE is venturing into a sky of uncertainty. We are only beginning to fly aircraft beyond our previous experiences. The current life prediction approach is not extensible to greater than 100%. A current Science and Technology Initiatives Program (STIP), funded by NAVSTO, is focused on providing reliabilities resulting from various actions and allowing the decision maker (operations commander) to heuristically weigh the consequences. These reliabilities go beyond crack initiation; they will be based on total life. This research and development is a natural progression in answer to the changing socioeconomic realities.

Total life is defined in Navy terms as a two-stage model. Normally cracks are modeled as having three distinct behaviors at three stages of life, nucleation, and growth as a small crack and growth as a large crack. Of course, the crack doesn't know what stage it's in, it simply responds to the driving forces that are thrust upon it! Our working definition of total life will encompass a two-stage model, crack initiation and growth. The two models are depicted in Figure 4. From our perspective the Navy has a need to consider the life of small cracks in the calculation of fatigue life, because small cracks will develop when aircraft are required to fly beyond an FLE of 100%. Consequently, this is an area where the greatest pay-off in modeling can come. Ironically, the Air Force also has a need to consider the life of small cracks, because that is the regime that will

gain them more life. Both services are working the same modeling problem but coming at it from the opposite ends of the life curve!

The total life concept is shown in Figure 5. The life of an aircraft is a random variable. We can not say with certainty how long an aircraft will fly without suffering a catastrophic failure due to cracking. Using a probabilistic approach to modeling, we can say with what probability of failure life can be obtained. Life is composed of two stages, as described by our model, initiation and cracking. The total life probability density function is a joint probability of times-to-crack initiation and the times to reach critical crack size at a critical location.

CONCLUSIONS

The Navy airframe structural integrity philosophy is to design, maintain and monitor our aircraft with the intent of precluding crack initiation. This philosophy is still relevant today, since unambiguous service life definitions and accurate tracking and predictive tools are the cornerstones to service life management and planning.

In those cases where effective planning was not achieved or adequate resources are not provided, probabilistic analysis must be performed in order to quantify the risks inherent in deviating from a rigid safe-life philosophy. Risk quantification is essential to minimizing dangers inherent in operating aircraft beyond design/certified service lives.

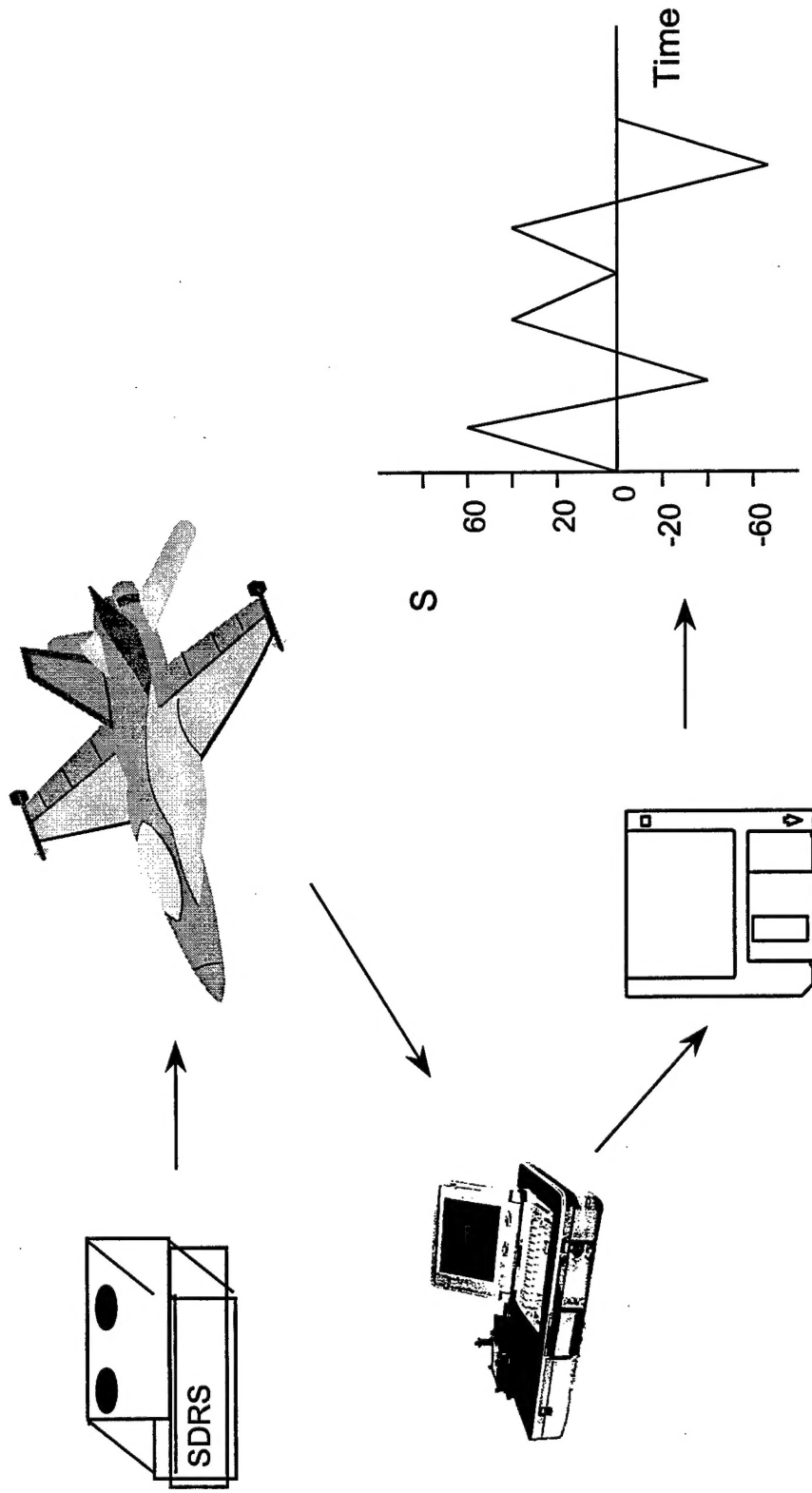
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Stress History at critical locations

Figure 1. The Fatigue Tracking Process: Data are downloaded from the aircraft and reduced to peak and valley stresses at critical locations.

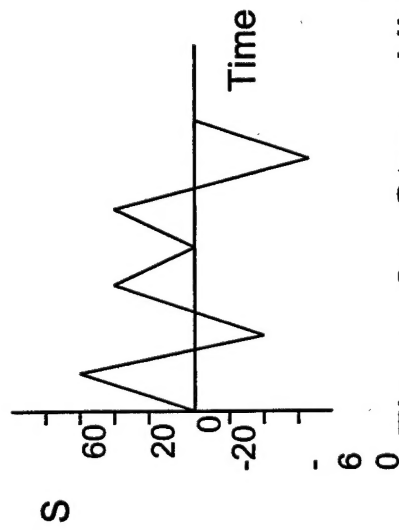


Figure 2a. Stress History

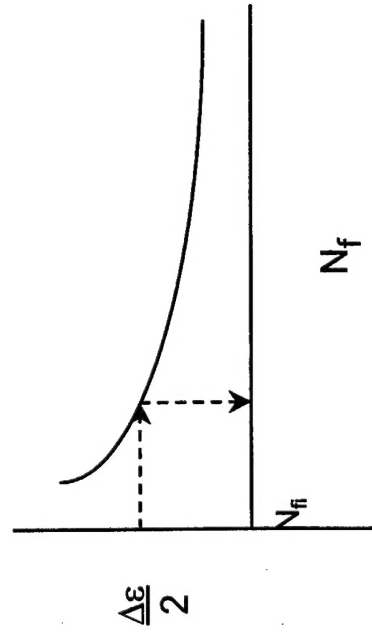


Figure 2c. Life determination from equivalent strain amplitudes.

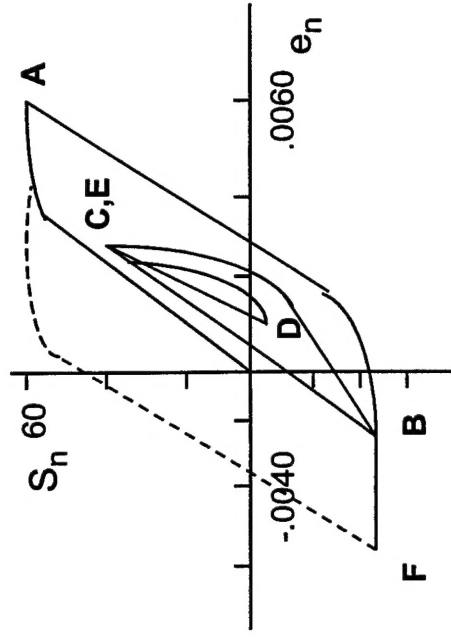


Figure 2b. Hysteresis Loops

$$\text{Damage} = \sum \frac{N_i}{N_f}$$

$$\text{FLE} = 200 * \text{Damage}$$

Figure 2d. Determination of FLE from Damage.

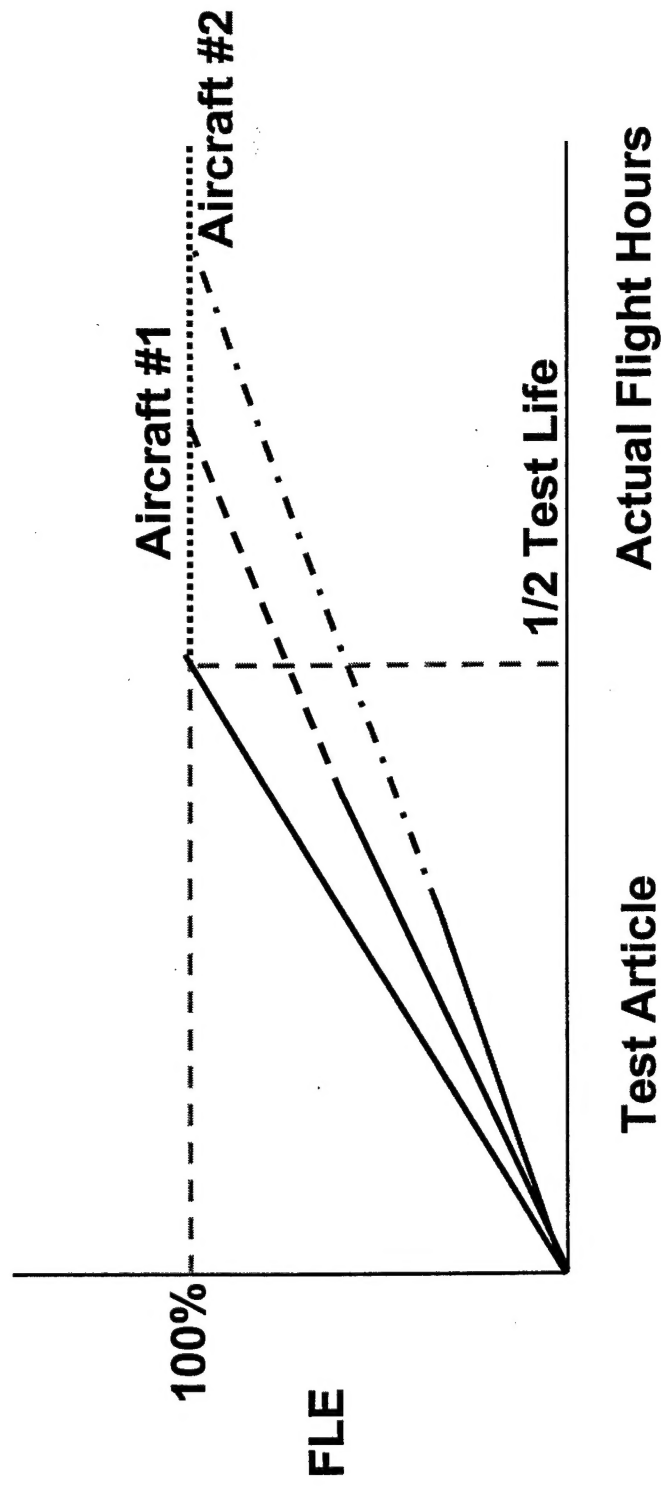
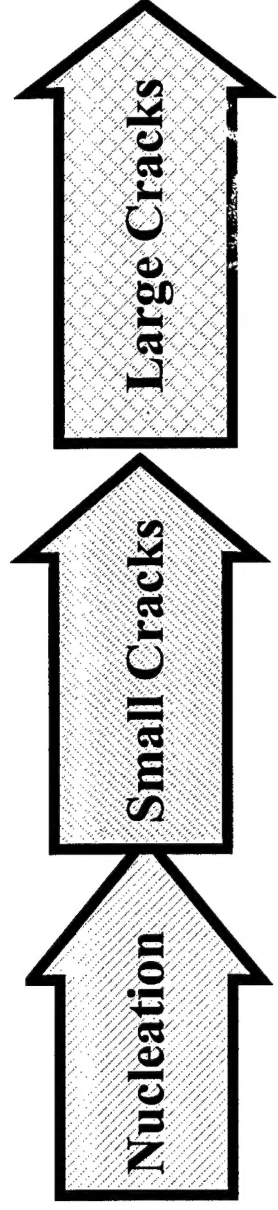


Figure 3. FLE is an index representing the portion of Fatigue Life Expended relative to the test article life. When viewed as a function of hours, the fatigue life can be estimated.

3-Stage Model



2-Stage Model

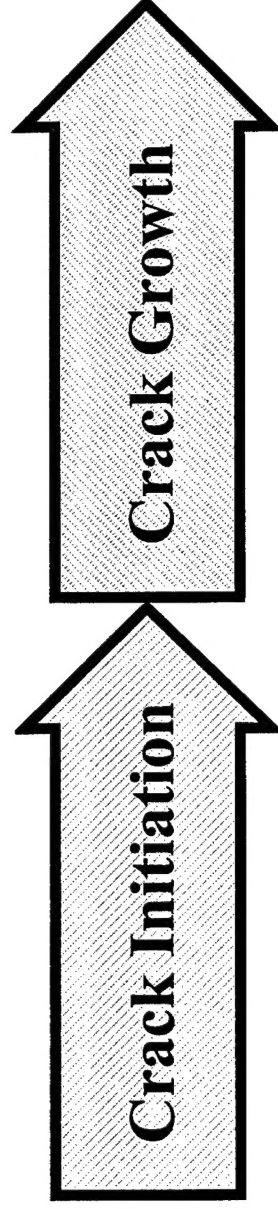


Figure 4. Total Life Definition

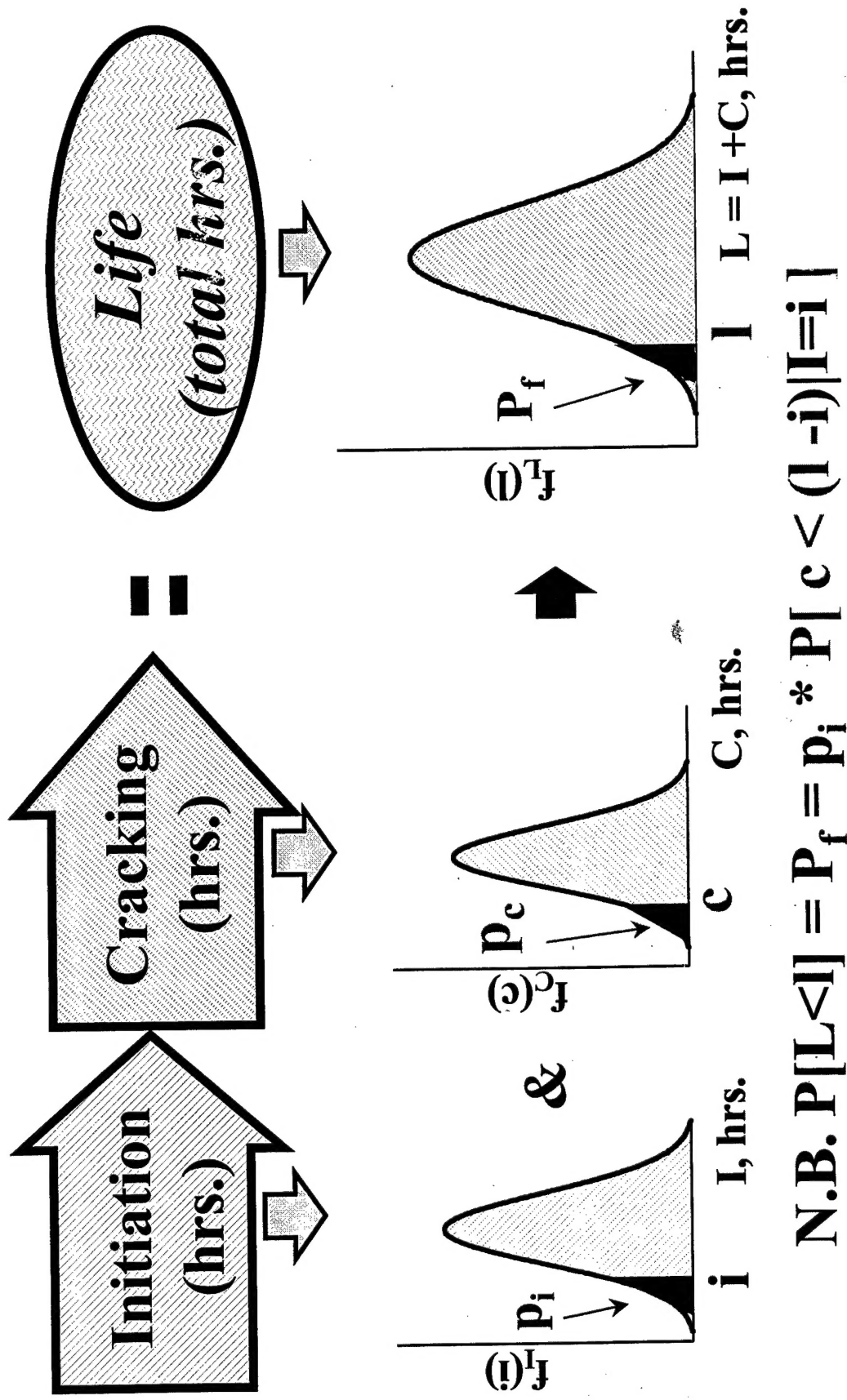


Figure 5. The Total Life Scatter, shown symbolically.